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Discussion Paper

Assessing the Potential and Feasibility of Carbon Dioxide Removal (CDR) Technologies in Saudi Arabia

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Executive Summary and Key Points

As the Kingdom of Saudi Arabia strives to achieve its climate goals and transition its economy away from fossil fuel dependency, understanding the viability and impact of carbon dioxide removal (CDR) options becomes paramount.

This paper reviews state-of-the-art CDR options and explores the potential applicability of such options within Saudi Arabia. Various CDR solutions, both conventional and novel, are investigated by using a multicriteria decision analysis (MCDA) methodology to compare CDR options relevant to Saudi Arabia. The MCDA methodology defines a set of performance, economic and environmental criteria. These criteria include technology readiness, CO2 permanence, current implementation costs, cost reduction options and environmental impacts. Further criteria include additional benefits from large-scale deployment, readiness of the policy and regulatory landscape, and ease of monitoring and verifying negative emissions. A tailored country-specific MCDA methodology can be a useful tool in deciding what CDR options are most relevant for a given country. In an analysis of Saudi Arabia, five groups of CDR options are identified. They are prioritized as follows: (i) energy-from-waste (EfW) and biomethane production with carbon capture, utilization and storage (CCUS), (ii) direct air capture (DAC), (iii) biomass pyrolysis with biochar production, (iv) conventional nature-based CDR and (v) enhanced weathering. EfW and biomethane sites with carbon capture and storage (CCS) offer CDR options that can be implemented by 2030, thus contributing to early CDR deployment. These options can help to establish the industry in its early stages. However, EfW and biomethane sites with CCS are estimated to account for only 20% of the required CDR needed to achieve net zero by 2060. Thus, by 2060, DAC will have to be the dominant CDR option, accounting for the remaining 80% of the requirement. To help achieve future CDR targets most effectively, sector- and technology-specific policies should be aimed at the deployment of such options, and optimal sites and locations for DAC should be fully assessed. On the basis of this comprehensive examination, this paper aims to provide insights and recommendations crucial for policymakers, researchers, and stakeholders in charting a sustainable pathway toward carbon dioxide removal in Saudi Arabia.

Keywords: Circular carbon economy, carbon dioxide removal, negative emission technology, CCUS, DAC, BECCS, energy-from-waste

1. Introduction

In the global context of combating climate change, achieving net-zero targets has become paramount for mitigating the adverse impacts of rising greenhouse gas emissions. The IPCC's comprehensive assessments highlight the urgency of attaining negative emissions, which are needed to limit increases in global temperatures in line with the goals of the Paris Agreement (Lee and Romero 2023). The Paris Agreement in 2015 and the subsequent IPCC Special Report on Global Warming of 1.5°C in 2018, which set net-zero targets and NDCs, have enabled many countries to set their own net-zero targets (IPCC 2018). However, policymakers worldwide realize that net-zero targets cannot be achieved without removing CO_2 from the atmosphere, whether directly or indirectly; key sectors, including heavy industry and aviation, present substantial decarbonization challenges and are unlikely to achieve net zero by midcentury. Carbon dioxide removal (CDR) technologies, also known as negative emission technologies (NETs), will thus play a pivotal role in offsetting residual emissions from challenging sectors that may persist even with aggressive decarbonization efforts. By actively removing carbon dioxide from the atmosphere, CDR technologies contribute to achieving the net-zero targets set by countries and organizations worldwide.

Scientific communities worldwide are increasingly researching CDR technologies and negative emissions; new technological advances and technical and economic studies are introduced regularly (Honegger et al. 2022). The integration of CDR technologies within modeling frameworks and studies is increasingly seen as crucial to complement emission reduction strategies and address the historical carbon debt accumulated in the atmosphere. These NETs encompass a range of approaches, some of which are conventional, such as afforestation, and others of which are emerging novel techniques (Smith et al. 2023), such as direct air capture (DAC), enhanced weathering, and biochar and bioenergy with carbon capture and storage (BECCS). Each method offers unique benefits and challenges; thus, a diversified portfolio of CDR solutions is necessary to fully address the climate crisis. As nations transition to a sustainable and carbon-neutral future, the incorporation of CDR technologies into national strategies is becoming necessary for navigating the complexities inherent to achieving global climate targets and securing a resilient planet for future generations. According to McKinsey & Company (Mannion et al. 2023), investment in the CDR industry could reach $1.2 trillion by 2050. Achieving such growth requires strong demand signals, clear policies, significant reductions in energy demand and associated costs, robust standards combined with transparent monitoring, reporting and verification (MRV) systems, and collaboration across the entire ecosystem.

The demand for CDR technologies extends globally, with countries worldwide recognizing their importance in achieving ambitious net-zero targets. A notable example is the Kingdom of Saudi Arabia (KSA), which, despite its historical dependence on oil and gas, has set forth an ambitious net-zero target for 2060 (Saudi & Middle East Green Initiatives 2023). Saudi Arabia aims to reduce its carbon footprint and transition toward a sustainable, diversified economy. In this pursuit, as part of Saudi Vision 2030, the Saudi Green Initiative (SGI) plays a pivotal role. It outlines a comprehensive roadmap to address environmental challenges and promote sustainable development. In recognition of the unique challenges faced by the KSA, the need for negative emissions and CDR technologies within the nation's decarbonization strategy is increasingly being acknowledged. With a commitment to sustainable practices and a growing awareness of the environmental impact of its industries, Saudi Arabia is exploring and investing in innovative solutions, including carbon capture and storage (CCS), afforestation, mangrove and wetland restoration and other CDR technologies. These solutions can play crucial roles in achieving the KSA's net-zero objective. The integration of such measures not only aligns with global efforts to combat climate change but also positions Saudi Arabia as a proactive participant in the global movement toward a sustainable and low-carbon future.

The geographic and climatic characteristics of Saudi Arabia present both challenges and opportunities for the deployment of CDR technologies. The arid climate and vast desert landscapes may pose difficulties for certain approaches, such as afforestation, while they could favor others, such as solar-powered DAC. Additionally, some options are energy intensive, and their limited potential may not justify large investments, which can be better directed toward CDR options with significantly higher CDR potential. In addition, some opportunities for CDR may align with the need to comply with sector-specific legislation (for example, the Saudi target to divert, by 2030, 19% of municipal solid waste from landfills to EfW plants). Understanding the strengths, weaknesses and opportunities for the various CDR methods is thus important for designing future policies that could, in the long-term, help achieve carbon removal in the most cost-effective manner in the context of the economy, society and environment. By critically assessing the suitability and potential of various CDR technologies in Saudi Arabia, this paper aims to provide valuable insights and recommendations for policymakers, researchers, and stakeholders. It seeks to contribute to the ongoing discourse on climate change mitigation strategies and assist in charting a sustainable pathway toward a low-carbon future for Saudi Arabia. By comparing the various CDR technologies on a common basis and utilizing a set of well-understood criteria, such complexities are transformed into actionable and practical measures.

Recent studies have used different tools to compare CDR technologies. Migo-Sumagang et al. (2023) reviewed the methodologies applied in the literature to compare CDR technologies up to 2023, including marginal abatement cost, multicriteria decision analysis (MCDA), machine learning, mathematical programming, pinch analysis and process graphs. Other researchers have proposed future models that included uncertainty, such as stochastic models, and mathematical programming for optimal implementation and operation. Bell et al. (2000) compared different MCDA methods applied to integrated assessments of climate change in the literature and concluded that such methods increase the insight and confidence of decision makers. Prütz et al. (2024), on the other hand, applied taxonomy maps to compare the cobenefits, challenges, and limits of CDR technologies. Some researchers have applied MCDA methodologies and highlighted the importance of applying such methodologies in evaluating the overall impact of CDR technologies. Other researchers have used MCDA methodologies to evaluate CDR technologies. Borchers et al. (2024) presented a recent and extensive analysis of CDR options for Germany and concluded that cover crops or seagrass restoration and BECCS are the most promising options.

Different researchers have applied MCDA to CDR assessment but with varying boundaries, objectives and scopes. Rueda et al. (2021) compared different CDR portfolios to achieve 1.5°C by 2100 and reported that the window of opportunity for achieving 1.5°C is quickly closing, and few meaningful advances have been made. Ma and Bai (2023) included the risks of nonadditionality, leakage, and reversal in their analysis. Tapia (2021) included the change in albedo resulting from CDR solutions in his MCDA model and reported that the solutions that increased albedo the most were biochar, afforestation, and BECCS.

Achieving net zero in Saudi Arabia requires the deployment of CDR technologies, as discussed in Section 2. Reviews of the CDR technologies currently being developed in the Kingdom clearly indicate that not all potential CDR technologies are being considered (see Section 2). There is, then, a need to develop an understanding of what CDR technologies are most applicable to the Kingdom and to rank these in terms of their readiness for deployment (i.e., which can be deployed by 2030 and which are longer-term solutions). To date, no study in the literature has applied the MCDA methodology to rank CDR options while considering a set of economic, environmental and technical criteria. Furthermore, no study has compared the relevance of various CDR options and their applicability in Saudi

Arabia. This study intends to fill this gap in the literature by undertaking an MCDA-based analysis of CDR options with a focus on Saudi Arabia. The application of MCDA to CDR options at this early stage of policy and strategy developments serves an important purpose. Its simplicity and time efficient nature can help policymakers quickly appreciate the barriers and limitations of various CDR options regarding conventional vs. novel solutions or nature-based vs. engineered solutions. This MCDA analysis provides the high-level of characterization needed to eliminate and exclude irrelevant solutions; however, MCDA needs support via further detailed analyses of costs and social and environmental impacts.

The paper is divided into five sections. Section 2 presents the MCDA methodology, while Section 3 details the criteria used to rank CDR technologies and presents the scoring methodology. Section 4 presents the analysis results and provides a high-level description of the potential of the top-ranking CDR options for Saudi Arabia. Finally, Section 5 highlights the main conclusions from this high-level analysis and introduces a set of recommendations to encourage deployment of the winning solutions.

1.1. Current CDR Development in Saudi Arabia

Saudi Arabia has emphasized in several international fora the importance of a circular carbon economy (CCE), in which "removal" is one of the four key principles (reduce, reuse, recycle, or remove) (Shehri et al. 2023). Recent work by KAPSARC suggests that a significant level of CDR will be needed to achieve net zero, with models suggesting 250-371 Mt/y by 2060 (Kamboj et al. 2023; Durand-Lasserve 2023). Currently, there is no legally binding or separate target for CDR in Saudi Arabia; however, the government is developing a strategy for the next steps in CDR policymaking.

Saudi Arabia is one of the cofounders of Mission Innovation on Carbon Dioxide Removals, launched in 2021, and, together with Australia, is leading the 2023-2026 Work Plan for the Enhanced Mineralization Technical Track, launched at COP28 (Birchall et al. 2023). In 2023, the groundbreaking Greenhouse Gas Crediting & Offsetting Mechanism (GCOM) was launched (Clean Development Mechanism Designated National Authority 2023). It aims to allow companies and organizations to offset their emissions by purchasing credits and certificates from projects that voluntarily reduce or remove greenhouse gas emissions. This scheme is expected to accelerate the deployment of CDR projects on the basis of a transparent methodology that prioritizes the most environmentally and economically attractive projects. Under this framework, accounting issues for CDR methodologies can be addressed by establishing requirements and specifications for the quantification, monitoring, reporting, verification, and registration of projects on the basis of GHG emission reductions and removals and by accounting for permanence and reversal of removals. In accordance with the government's plans, the GCOM will adapt to future changes and developments at the national and international levels, including alignment with Article 6 of the Paris Agreement.

Saudi Arabia is also leading globally in terms of other technologies, which are enablers for large-scale engineered CDR. The development of CCS infrastructure is a requirement for the wide-scale deployment of large-scale engineered CDR technologies such as DAC and BECCS. The Kingdom's target is to capture and permanently store 9 Mt CO_2/year by 2027 and 44 Mt CO_2/year by 2035. This CCS volume requires the development of complex and expensive infrastructures, which will eventually be utilized for DAC and BECCS plants in the future. In addition, other work has been undertaken in the Kingdom to help understand the overall potential for CCS. Recent work has evaluated CO_2 emissions from various sources (Hamieh et al. 2022) and the availability and suitability of CO_2 geological storage (Jing et al. 2023). These studies pave the way for a comprehensive understanding of CCS potential in the Kingdom and ultimately for the development of the CCS and CDR industries.

Some examples of CDR investments in the Kingdom are described in **Table 1**. Further projects on DAC are also being evaluated with the aim of scaling up DAC deployment in Saudi Arabia in the next decade. Notably, the deployment of CDR technologies within the Kingdom is not without significant challenges, which need to be well understood and evaluated before wide-scale deployment. An assessment of all CDR options in a country and an evaluation of country-specific challenges and barriers and anticipated benefits can aid in the drafting of a CDR roadmap and lead to the cost-

Table 1. CDR projects under development in Saudi Arabia.

CDR option	Description	Location	CDR type	Reference
Enhanced mineralization (land)	In-situ mineralization involving dissolving CO_2 in water and injecting in the ground to form carbonate rocks.	Jizan	CO_2 source and sink	(Aramco 2023)
Climatree – a DAC technology	Aramco with partners Greengroves developed this DAC system, which comprises carbon capture with microalgae photobioreactor integrated with a CO_2 scrubber. This is now being piloted.	Al Qurayyah	CO_2 source	(Aramco Life 2022)
DAC-Aramco-Siemens collaboration	Aramco and Simens are collaborating on trying to demonstrate DAC in the Kingdom.	Dhahran	CO_2 source	(Picciotto 2023)
Wetland restoration	The first mangrove eco-park in the Kingdom, which protects 64 km^2 of marine habitats, was developed by Aramco.	Arabian Gulf coastline	CO_2 source and sink	(Aramco 2024)
Afforestation	This includes planting 10 billion trees and rehabilitating 40 million hectares of land by 2060. The National Center for Vegetation Development is responsible for this initiative.	Middle East & Saudi Arabia	CO_2 source and sink	(Saudi & Middle East Green Initiatives 2024)

effectiveness of the full CDR potential. This paper aims to achieve this objective by gathering evidence and assessing the various CDR options (not limited to those shown in Table 1) available to Saudi Arabia.

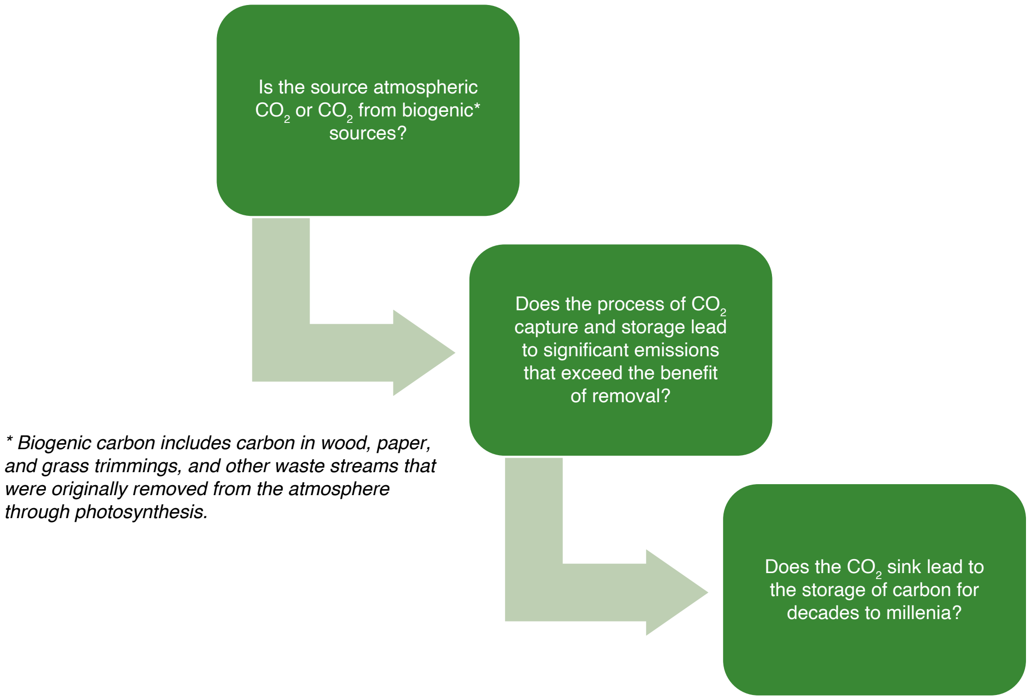
1.2 Review of CDR Options

CDR (also referred to as carbon removals, greenhouse gas removals, GGRs, or NETs) encompasses processes that involve removing CO_2 from the atmosphere, directly or indirectly, and storing it permanently for long periods, ranging from decades to millennia (Smith et al. 2023). CO_2 storage duration (or permanence) refers to the longevity of carbon storage achieved through these methods and ensures that the captured carbon remains sequestered. In this work, we consider systems that can store carbon for at least 100 years to have medium to high permanence.

A CDR process (e.g., afforestation) should be additional to Earth's processes and a result of human intervention (Smith et al. 2023). In addition, in evaluating the feasibility of a CDR option for achieving negative emissions, three main principles need to be considered in detail (see Figure 1). These are as follows:

- **The source of CO_2**: Whether the process involves CO_2 removal, whether directly or indirectly, from the atmosphere.
- **The process itself and its associated life cycle impacts**: Whether the process consumes energy at levels leading to carbon emissions that exceed those removed through the process itself and whether the life cycle impacts are significant to the point that the process negates the benefit of removing emissions.
- **The CO_2 sink**: Whether the process leads to actual storage of CO_2 for long periods as opposed to releasing CO_2 back into the atmosphere (e.g., synthetic fuels).

Figure 1. Considerations in defining a CDR process.



Source: KAPSARC.

A CDR option is considered a carbon removal process if the CO_2 source is either atmospheric CO_2 or of biogenic origin (i.e., a bioenergy source). In processes where there is demand for energy input, the process needs to provide net carbon removal; thus, the source of energy (whether low-carbon or fossil fuel-based) and impacts of the life cycle of the process (upstream and downstream emissions) should be considered when deciding whether a process is actually a CDR option that leads to negative emissions. This type of analysis usually needs to be undertaken on a case-by-case basis.

CO_2 sinks can be either land-based or ocean-based. Land-based sinks include geological formations, soil and vegetation and agriculture. Ocean-based sinks include CO_2 dissolved in the ocean or stored in marine vegetation. Storage may also be performed in manufactured industrial products (bricks, concrete, and polymers) or in construction wood.

CDR technologies encompass a range of technologies and approaches designed to actively remove CO_2 from the atmosphere and thus effectively counter the effects of past anthropogenic emissions. The State of Carbon Dioxide Removal report (Smith et al. 2023) and Ricardo Energy and Environment report (Leishman et al. 2023) provide a comprehensive overview of CDR technologies.

Table 2 shows the various routes for removing carbon dioxide from the atmosphere. Within the realm of CDR, a spectrum of technologies exist, ranging from conventional CDR systems to novel, cutting-edge approaches. Conventional CDR systems often involve natural processes, such as afforestation and reforestation, which leverage the carbon sequestration capabilities of forests and ecosystems. On the other hand, novel CDR systems utilize advanced technologies such as DAC, enhanced weathering, BECCS, and biomass pyrolysis with carbon storage in biochar. State-of-the-art technology in CDR reflects a dynamic landscape of innovation, with ongoing research and development striving to optimize efficiency, scalability, and economic viability. However, these advancements are not without their challenges and barriers.

Conventional methods may face limitations in terms of the availability of suitable land and the extended timeframes required to achieve significant carbon sequestration. While promising, novel technologies may encounter obstacles related to high implementation costs, high energy consumption, and potential environmental impacts, such as the use of chemicals. Additionally, the deployment of large-scale CDR systems necessitates overcoming regulatory, economic, and social barriers. Recognizing and addressing these challenges is crucial for the successful integration of CDR solutions into comprehensive climate action plans, ensuring that both conventional and novel systems contribute effectively to global efforts in achieving sustainable and lasting carbon removal.

As nations such as Saudi Arabia navigate their net-zero objectives, a nuanced understanding of the state of CDR technologies and the associated challenges will be instrumental in shaping effective and adaptable climate policies.

The various CDR options vary in technological readiness level (TRL), costs, global potential and monitoring, and MRV-readiness. The data presented in Table 2 summarize these four parameters for the various CDR options categorized as follows: land-based conventional CDR, land-based novel CDR (i.e., the three engineered solutions as well as enhanced weathering) and ocean-based CDR. The data presented in Table 2 are based on a review of the literature and show variations in costs, TRLs, the availability of MRV guidance, and the precision of the available measurement techniques (Smith et al. 2023; Marrion et al. 2023).

Ocean-based approaches are generally characterized by a combination of low TRLs, a lack of MRV guidance, and low precision in measurement techniques. Thus, such methods are not expected to play a key role in carbon dioxide removal in the near future and are not further considered in this analysis for Saudi Arabia, which considers only options with TRLs>3. The information summarized in Table 2 is used as the basis for ranking technologies in terms of their relevance for Saudi Arabia.

Table 2. Range of CDR options discussed in the literature.

CO_2 Source and CDR Category	Direct Removal Medium	Process	Storage	Type of CDR	Description	Technology Readiness Level (TRL)	Global Potential (Gt CO_2/y in 2050)	Levelized Costs Range in Literature ($/t CO_2 Removed)[1]	Score for Availability of MRV Guidance[2]	Scores for Precision of Measurements[2] (Capture, Storage)[3]	MRV Readiness Level (MRL)[4]
Atmospheric CO_2											
Land-based Conventional systems											
	Agriculture / forests / crops / food / grasses / waste products	Natural	Biomass	Afforestation	Direct storage of atmospheric CO_2 in biomass	9	10	0-240	6	3,3	15
	Soil	Natural	Soil	Soil sequestration	Direct storage of atmospheric CO_2 in soil	9	9.3	0-100	6	2,1	8
				Wetland restoration		9	2.1	Not available	6	1,1	8
		Natural	Wood products	Wood used in construction		9	1.3	Not available	6	3,2	12
Land-based Novel	Agriculture / forests / crops / food / grasses / waste products	Combustion / Gasification / Anaerobic digestion / fermentation	Storage of CO_2 in saline aquifers, depleted oil and gas fields, minerals[6] or in products from industrial processes, i.e., bricks, aggregates)	Bioenergy CCS (BECCS)[5]	Bioenergy conversion combined with CCS	5-9	11	15-400	6	3,3	15
		Pyrolysis		Biochar	Approximately 50% of carbon in biomass can be stored in biochar	7	7	10-345	6		12

CO_2 Source and CDR Category	Direct Removal Medium	Process	Storage	Type of CDR	Description	Technology Readiness Level (TRL)	Global Potential (Gt CO_2/y in 2050)	Levelized Costs Range In Literature ($/t CO_2 removed)[1]	Score for Availability of MRV Guidance[2]	Scores for Precision of Measurements[2] (Capture, Storage)[3]	MRV Readiness Level (MRL)[4]
		Direct air capture	Storage of CO_2 in saline aquifers, depleted oil and gas fields, minerals, or in products from industrial processes	DAC	Chemical CO_2 capture (liquid- or solid-based) CO_2 can be used to produce fuels or chemicals, or it can be stored permanently	6	40	600-1000	3	3,3	12
	Rocks / minerals	Natural	Rocks / minerals	Enhanced weathering[6]	Direct storage of atmospheric CO_2 in rocks and minerals	4	4	5-200	0	1,1	1
Ocean-based Novel	Ocean	Natural	Ocean water	Ocean fertilization	Direct storage of atmospheric CO_2 in the ocean through chemical and biological processes)	2	100	40-260	0	1,1	1
				Ocean Mineralization		2	3	50-500	0	1,1	1
			Ocean vegetation	Coastal wetlands / blue carbon		3	1	Not available	0		2

Notes

1 Afforestation and soil sequestration are reported in the literature to have no net costs (IPCC AR6 WGIII). In such cases, carbon credits or incentives, enhanced crop productivity or other cobenefits outweigh the costs of maintenance and implementation of these CDR options.

2 Availability of MRV guidance for both the capture and storage processes (6 = available for both, 3 = available for either, 0 = not available for both).

3 Precision of measurements for both the captured (high precision = score of 3, medium precision = 2, low precision =1) and stored CO_2 (high precision = score of 3, medium precision = 2, low precision =1).

4 A score of 1-15 is based on the availability of MRV guidance (a score of 0, 3 or 6 as in 1 above) and the precision of the measurements in the capture and storage processes (a score of 1-9, which constitutes the multiplication of the capture and storage scores).

5 BECCS can be divided into many types depending on the sector of applications. Power BECCS, EfW BECCS, biomethane BECCS, Industry BECCS, biofuels BECCS, etc.

6 Mineral carbonation refers to mineral processes in industry where CO_2 originating from industrial processes remains trapped permanently in products such as concrete blocks, green cement and aggregates where enhanced weathering is also a mineral carbonation process but with the CO_2 coming directly from the atmosphere (enhanced natural process).

2. Methodology

Figure 2 presents the methodological framework applied in the paper. Stage 1 involves a review of the potential role of CDR technologies in Saudi Arabia, as discussed in Section 1. This leads to the creation of a list of CDR technologies with significant potential in Saudi Arabia.

The current analysis and comparison of CDR technologies is based on an MCDA methodology. Stage 2 consists of the selection and description of the MCDA methodology, decision-making goals, criteria, weights and scores, as discussed in this section (Section 2). Notably, the MCDA considered here is intended to provide a high-level analysis to identify and compare key differences among CDR technology deployments in Saudi Arabia. This analysis should be supported by detailed analysis to determine the potential of the various CDR technologies.

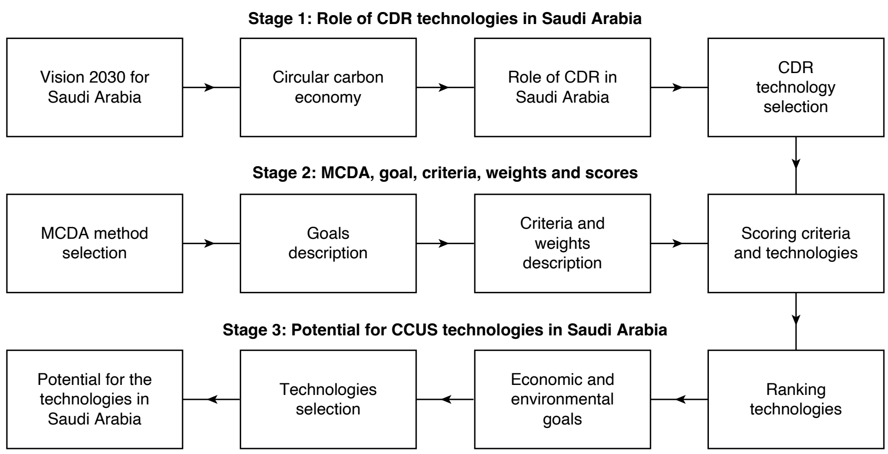
Stage 3 presents the potential for CDR technologies in Saudi Arabia and ranks them in terms of both economic and environmental goals, as discussed in Section 3.

The MCDA methodology used for this analysis utilizes simple additive weighting (SAW). This approach improves the comprehension and transparency of a complex analytical problem for the decision maker. More details on the methodology can be found by referencing Wang et al. (2009). The main steps for the current MCDA methodology include the following:

- defining the goals of different decision makers
- dentifying and characterizing key CDR technologies
- defining the criteria used to compare the different technologies
- defining the scoring methodology and weights of the various criteria.

The SAW is an approach used to address the multiattribute decision-making conundrum. At its core, the SAW technique involves computing the total of the weighted evaluation scores for every technology across all criteria.

Figure 2. Methodological framework applied in the paper.



Source: KAPSARC.

Implementing the SAW method necessitates normalization of the decision matrix to a standardized scale, thus facilitating comparisons with the ratings assigned to available alternatives. This process enables various alternatives to be compared with the best performing alternative, i.e., that with the highest score. When dealing with the normalized score (r_{ij}) of a technology (*i*) and criteria (*j*), Equation 1 is employed, denoting a number from 0 to 1. To determine the criteria weights (w_j), Equation 2 is applied. The current analysis assumes a 3-point scoring system for each criterion with a "high/medium/low" ranking.

The ranking of the technologies (V_i) is then calculated with Equation 3, where *n* is the number of criteria considered in the decision process.

$$r_{ij} = \frac{x_{ij}}{Max(x_{ij})} \tag{1}$$

$$w_j = \frac{w_j}{w_1 + \cdots + w_j} x\ 100\% \tag{2}$$

$$V_i = \sum_{j=1}^{n} w_j\, r_{ij} \tag{3}$$

Table 3 lists the various CDR technologies considered for this study. Each of the options effectively defines a source (either atmospheric CO_2 or CO_2 from biogenic sources), a CO_2 sink or a process. Three options are considered for the permanent storage of CO_2 from DAC. In mineral carbonation (Option 7, DACMC, in the table below), a concentrated CO_2 stream is used to speed up the mineral carbonation process, whereas in enhanced weathering (Option 11, EW), the same exact process occurs but utilizes atmospheric CO_2 directly from the atmosphere, so the process occurs at a slower rate due to the lower concentrations.

With respect to criteria selection and for simplicity, reducing the subjectivity of the decision process as much as possible is desirable. For this reason, the criteria weights are not included in the analysis; thus, the MCDA process is designed to weight the impacts of all the criteria equally in the decision process. For this reason, only criteria that have a substantial effect on the final decision are selected.

Following a comprehensive review of the literature, data and information on the various CDR options are collected. We score each of the CDR options as high, medium, or low on the basis of a set of criteria described in Table 4. This approach makes the decision process as simple, transparent, and unbiased as possible.

Table 3. List of CDR options considered for this study.

Code	CDR technology
1	Afforestation (AF)
2	Soil sequestration (SS)
3	Wetland restoration (WR)
4	Wood for timber in construction (WfC)
5	Energy-from-waste with carbon capture and storage (EfW BECCS)
6	Anaerobic digestion of waste with CO_2 utilization (BM BECCU)
7	Biochar (BC)
8	DAC with CO_2 geological storage (DACCS)
9	DAC with CO_2 utilization in concrete and brine (DACCU)
10	DAC with mineral carbonation (DACMC)
11	Enhanced weathering (EW)

Table 4. Criteria used to compare the different CDR technologies.

Criteria	Criteria Description	Metric	Score (L, M, H)*	Comments on Scoring
Technology readiness level (TRL)	Level of technology maturity	1-3	L	Scoring: (L, M, H) were determined with reference to the TRL data in Table 2. General Trend and Assumptions: Conventional CDR technologies have higher TRLs and are better understood. In general, a higher TRL means a more established supply chain and skill set. Considerations: How advanced is the option/technology currently? What is in planning for demonstration and scale-up?
		4-6	M	
		7-9	H	
CO_2 permanence and durability (years)	Period for which the CO_2 captured from the atmosphere will be stored	0-100 years	L	Scoring: Data for permanence is based on analyses of various sources provided in the literature on the permanence of CO_2 storage. General Trend and Assumptions: Biological storage and nature-based systems will have lower permanence and durability while geological storage (e.g., in saline aquifers) is associated with long periods. For this analysis, we assume CO_2 storage in carbonates (e.g., concrete blocks) is close to 1,000 years. Considerations: What is the permanence in years? What is the likelihood of leakage?
		101-10,000 years	M	
		10,001-100,000 years	H	
Costs (USD/t$CO_{2)}$ and cost reduction potential	Cost of removing 1 ton of CO_2 from the atmosphere (CurrentC) and probability for cost reduction (ProbCoRed) in next decade (Low, High)	CurrentC: > $500/t ProbCoRed: Low	L	Scoring: Current cost data is based on Table 2 gathered from the literature. Saudi specific circumstances influencing CapEx and OpEx are also considered. General Trend and Assumptions: Costs of novel engineered solutions are higher than conventional CDR solutions. Engineered solutions are likely to witness significant cost reductions following commercialization (learning curves based on other similar technologies). Considerations: What are the current costs considering variation in the literature? How likely are the costs to reduce in the next decade, measured by projects in planning for scale-up and similarity to other technology trends?
		Current C: > $500/t, ProbCoRed: High	M	

Criteria	Criteria Description	Metric	Score (L, M, H)*	Comments on Scoring
		CurrentC: $150-500		
		Current C: < $150	H	
Environmental impacts	Life cycle emissions, air pollution, land requirement and natural resources consumption	High impact	L	Scoring: The assessment here is based on the literature reviewed for this study. General Trend and Assumptions: CDR technologies lead to CO_2 removal but the negative emission potential depends on the life cycle emissions and other environmental impacts. For example, engineered solutions cause pollution through the use of energy and chemicals. Considerations: What are the upstream and downstream processes? What are the energy requirements and potential GHG emissions associated with these processes? Does the CDR process directly or indirectly lead to nitrogen and sulfur oxides and particulate matter increase? Is the CDR process likely to lead to water pollution? Are there any impacts on biodiversity and the ecosystem? Does the CDR process require mining? Is the area and space footprint significant?
		Low impact	M	
		Positive impact	H	
Enabling policies and regulations	Whether specific policies and regulations in Saudi Arabia exist or whether enabling	None	L	Scoring: This is based on reviews of the status of various initiatives in Saudi Arabia. General Trend and Assumptions: CDR policy and strategy for the Kingdom is still in development and so all CDR options are assumed equal in terms of the development of the overarching CDR policy. Differentiations are made in terms of technology- or option-specific policy and regulation. CDR options already being deployed (e.g., mangrove initiatives, tree plantations) are given a high score. Engineered solutions require significant CCS infrastructure, and their enabling regulations and policies are still in development. Existing initiatives which could encourage certain options are also considered (e.g., the initiative to divert municipal solid waste from landfills to EfW plants could facilitate the emergence of EfW BECCS and biomethane with CCS as CDR options). Considerations: What policy and regulation need to be in place to accelerate deployment of the CDR option? What is the current status of the specific policy and regulation? What are the gaps? Is there enabling policy which paves the way for future deployment?
		Under development or some enabling policy	M	

Criteria	Criteria description	Metric	Score (L, M, H)*	Comments on scoring
		Existing or real project deployment underway	H	
Existence of MRV guidance and precision	Considers (i) existence of MRV guidance which are essential for a CDR option to contribute to negative emissions, and (ii) the precision of measuring techniques. Total score (1-15)is as described in the last column.	< 8	L	Scoring: Two parameters (both shown in Table 2) are considered here: (i) the availability of MRV guidance (score 0–6) and (ii) the precision of measurements in capture and storage processes (score 1–9). General Trend and Assumptions: The methodology for estimating MRV readiness level is based on the total of two scores (measurement precision and MRV guidance regarding the state of development) as described by footnotes 1–3 under Table 2. Only afforestation and BECCS score higher than 12; DAC and biochar score between 9 and 12; and several nature-based solutions have lower scores. Overall, conventional methods, despite being well-developed, still score low. Novel engineered solutions score higher, as these processes can be easily monitored and much of the necessary guidance is already in place. Considerations: What is the current MRV readiness score based on the system described above?
		9-12	M	
		> 12	H	
Applicability to Saudi Arabia	This criterion describes how suitable a technology is to Saudi Arabia.	Low suitability	L	Scoring: This is based on level of suitability for KSA. General Trend and Assumptions: Conventional large-scale engineered solutions are suitable for Saudi Arabia due to its well-established oil and gas infrastructure and industry. BECCS, in general, is not completely suitable due to the shortage of bioenergy crops. However, in the presence of waste feedstocks and emerging legislation to encourage waste management and diverting waste from landfills, EfW BECCS becomes an attractive option in combination with well-established industry. Biochar, on the other hand, is small scale and requires a specific skill set but is still suitable for waste feedstocks. Considerations: Considering all of the above in terms of technology, economic, environmental and MRV aspects, as well as country-specific circumstances (e.g., water availability, space requirements, readiness of enabling policy, cost of energy, availability of renewable resources, etc.), how suitable is the specific CDR option to KSA?
		Mid suitability	M	
		High suitability	H	

Criteria	Criteria Description	Metric	Score (L, M, H)*	Comments on Scoring
Cobenefits to Saudi Arabia	This criterion describes the direct and indirect benefits to the economy and society for the development the CDR technology	Low benefits	L	Scoring: This is based on whether the benefits are significant or have very low impacts. General trend and assumptions: All CDR options are assumed to provide additional environmental benefit in terms of carbon removal. This criteria considers their additional benefits. Benefits evaluated include job creation potential and GVA. In general, engineered solutions score relatively high here due to the large and complex infrastructure involved. Biochar systems, while small scale, also offer benefits in terms of the ecosystem and soil reconstruction. Biomethane-CO_2 and DAC-CO_2 utilization in concrete bricks and for other products offers additional revenue streams but needs to ensure applications with permanent storage in products. Considerations: What additional economic benefits does a specific CDR option provide to the KSA? What is the potential for future revenue streams in the market for companies? What are the possibilities for job creation? What is the quality of the jobs and how long are they likely to last? What is the impact on local economies as well as at the national level? What is the impact at the global level that the development of the CDR in question will have on the Kingdom?
		Mid benefits	M	
		High benefits	H	

Notes:
* In applying equations 1–3 above: L = 0, M = 0.5 and H = 1.

3. Results

Using the data and information gathered in Section 1 and applying the methodology and criteria described in Section 2, we analyzed the potential and suitability of various CDR technologies for Saudi Arabia. The MCDA methodology selected is universal in that it can be applied to countries and regions worldwide to establish the best and most appropriate CDR solutions for a given country or region. The results of the analysis for Saudi Arabia are shown in Table 5.

Table 5 shows that the various CDR options can be broken into five groups in terms of overall performance.

1. **Group 1 (BECCS)** has the highest scores (both for biomethane and EfW BECCS) because of its relatively high TRL, relatively easy ability to be understood and relatively low costs with potential for future cost reduction (if innovative chemical solvents are developed). Furthermore, this group is characterized by well-understood MRV processes, the potential for creating jobs in the waste and CCUS sectors, and existing policies to divert waste from landfills to waste management plants.

2. **Group 2 (DAC)** is currently an expensive technology but scores higher than conventional nature-based solutions because of its potential for controlling the fate of the captured carbon dioxide (whether via storage in saline aquifers, mineral carbonation or industrial applications where it remains stored, i.e., concrete blocks). This group y is suitable for Saudi Arabia owing to the low cost of energy needed to run these processes as well as the lower costs of CO_2 transport and storage. DAC could also play a key role in establishing a new industry with opportunities for new jobs and significant added value to the Saudi economy.

   DAC, regardless of the sink for the captured CO_2, is an attractive option for Saudi Arabia because of the inherent flexibility in locating the relevant plants, the significant potential for carbon removal and the possibility for cost reduction in the future. DAC is energy intensive, but the availability of renewable sources in Saudi Arabia could play a key role in reducing costs and maximizing the negative emission potential of DAC. Further investigation of how these renewable sources can be utilized and where DAC clusters should be located is a priority for Saudi Arabia.

3. **Group 3 (biochar)** is a relatively established technology with several plants operating worldwide, mainly in Europe. However, further demonstration of this technology is needed. A significant proportion of the CDR credits currently being sold are biochar credits. Biochar can have a positive impact on the environment, as it can be used for soil reconstruction and mixed with compost or used as animal feed. However, biochar scores lower than other CDR options in Saudi Arabia because of the absence of legislation and policy to encourage its production and use. Guidance for monitoring and verifying the amount of carbon captured and stored in biochar still needs to be further developed.

4. **Group 4 (conventional nature-based solutions)** are high in TRLs and generally low in cost (albeit some of the costs are poorly understood) but are associated with potential environmental impacts, less established MRV techniques and guidance and, in general, lower durability. They vary in their suitability and potential in Saudi Arabia. Planting 10 billion trees is the right policy for the Kingdom, but it will require significant amounts of water, which could lead to significant environmental impacts. As a result, there is a need to explore afforestation and vegetation further to identify the various challenges

Table 5. Decision matrix for comparing CDR technologies in Saudi Arabia.

CDR Technology	Technology Readiness Level (TRL)	CO_2 Permanence and Durability	Costs in KSA	Environmental Impact	Established Policies and Regulations	MRV Guidance and Precision	Suitability to Saudi Arabia	Cobenefits to Saudi Arabia	Ranking by Group
Afforestation	H	L	L	H	H	H	M	M	4
Wetland restoration	H	L	H	H	H	L	M	H	
Soil carbon sequestration	H	L	H	H	L	L	M	L	
Wood products	H	L	H	H	L	M	L	M	
BECCS (EfW) and permanent storage	M	H	H	M	M	H	H	H	1
BECCS (biomethane) and concrete storage	M	H	H	M	M	H	H	H	
Biochar	H	M	H	H	L	M	M	H	3
DAC and permanent storage	M	H	M	M	M	M	H	H	2
DAC and concrete storage	M	H	M	M	M	M	H	H	
DAC and Mineral carbonation	M	H	M	M	M	M	H	H	
Enhanced weathering	L	H	H	L	L	L	L	L	5

Abbreviations: H: high; M: medium; L: low.

and barriers to deployment. Wetland restoration, which is currently occurring at various locations across the Kingdom, provides environmental benefits while also helping create jobs. Saudi Arabia has many mangroves, wetlands, mountain forests, and meadows. Afforestation is part of the future roadmap to plant 10 billion trees in the Kingdom and enhance vegetation cover across urban areas and various habitats. Between 2017 and 2023, more than 40 million trees were planted across the Kingdom. However, its significant water demand caused this option to score lower than other CDR options.

5. **Group 5 (enhanced weathering)** scores lowest of the options, mainly because of the immaturity of technology; lack of policies and regulations, which are necessary to facilitate the deployment of this technology; lack MRV guidance; and potential environmental impacts. In addition, EW has a low TRL, and although costs are reported as lower than some engineered solutions, there is currently no research on the cost drivers and how such costs can be further reduced. Further work is needed to study the status of EW, its associated costs, and its potential benefits to the Kingdom.

In summary, this analysis reveals that engineered solutions score higher than nature-based solutions for Saudi Arabia. BECCS has limited opportunities in general, but when applied to EfW plants, it offers short- to medium-term opportunities. Furthermore, emerging legislation encourages it, and many plants are also being planned worldwide. Regardless of the storage option, DAC with permanent storage (DACCS) also scores high because of its high potential in the Kingdom (see Section 5) and the ease of monitoring and verifying it. Although this technology is currently very expensive, it has significant potential for cost reduction as learning increases over time. Conventional nature-based solutions, in general, comprise many well-established technologies. However, they are characterized by a limited understanding of costs, less durability of the stored carbon and limited potential in terms of carbon dioxide removal in the Kingdom. Several of these options are also associated with environmental impacts and externalities, including high demands for water, impacts on the ecosystem and biodiversity, and the potential release of nitrous oxide. In addition, the majority of nature-based conventional solutions have less established MRV procedures, as they are more difficult to control than are engineered solutions.

Section 4 focuses on engineered solutions (BECCS, DAC and biochar) and highlights their potential for achieving CDR targets in the future in Saudi Arabia.

4. Discussion

As highlighted above, owing to the limitations of conventional nature-based solutions in Saudi Arabia, novel engineered solutions such as BECCS, DAC, and biochar play important roles in CDR. However, these solutions have their own set of limitations. Despite their current TRL levels and high costs, engineered solutions offer advantages in terms of ease of monitoring and verification and the potential to control and reduce environmental impacts. Having a clear MRV methodology with high precision is particularly crucial for ensuring transparency and accountability in carbon removal efforts. In addition to their environmental benefits, these technologies have the potential to spur technological innovation, create employment opportunities, and diversify the nation's economy. Strategic investments and collaborations, both domestically and internationally, can catalyze the development and deployment of CDR solutions, thereby fostering a thriving ecosystem for sustainable innovation and economic growth. For engineered CDR technologies to play their anticipated roles, a wide range of challenges and barriers need to be overcome. These are highlighted below.

4.1 Opportunities for BECCS in Saudi Arabia

Saudi Arabia is not rich in bioenergy sources, so the adoption of BECCS as a CDR solution may seem unattractive. However, diverting waste from landfills to waste incineration and anaerobic digestion (AD) plants and equipping these plants with carbon capture and permanent storage offers opportunities for the Kingdom to achieve some of its CDR targets through BECCS (Odeh 2024; Hayat et al. 2023).

EfW (i.e., waste incineration plants with power and heat production) can play a key role in both waste management and, when equipped with CCS, carbon removal. The implementation of a waste management strategy that emphasizes waste diversion from landfills could significantly increase the effectiveness of these technologies. An EfW plant consists of a boiler and steam turbine, similar to a BECCS power site. EfW differs from other power plants in terms of fuel input, which may include municipal solid waste (MSW) and commercial or industrial waste. Therefore, the fuel varies in terms of moisture content, calorific value and biogenic fraction (40% to 60%).

EfW plants with CCS are planned globally in Scandinavia, in the UK, and across Europe. Postcombustion capture (typically using amines or carbonate solutions) is the CO_2 capture technology of choice. The challenges of equipping EfW with CCS are discussed in detail by Gibbins and Lucquiaud (2022). The costs reported for EfW with CCS can be as low as \$102/t CO_2, and when operating as combined heat and power plants, the costs can be \$65-70/t CO_2 (Aramco 2024). Such plants can provide an opportunity for Saudi Arabia to achieve negative emissions until other engineered solutions, such as DAC, become less expensive.

A recent study by KAPSARC (2024) estimates that 8.8 Mt CO_2/y CDR capacity can be achieved by 2040 by equipping new EfW plants in the Kingdom with CCS (on the basis of current waste volumes and 19% diversion of MSW from landfills to EfW plants by 2030, as announced). This is an important opportunity for Saudi Arabia to kickstart the CDR industry.

A comprehensive waste management plan in Saudi Arabia can also provide opportunities for biomethane production, either through thermochemical routes (waste gasification to produce syngas followed by methanation) or through biological processes (i.e., in AD plants to produce biogas followed by CO_2 removal or capture to produce methane). For AD plants, manure sewage sludge and food waste can serve as feedstocks. Thousands of AD plants exist worldwide, many of which upgrade biogas (by CO_2 removal) to produce biomethane. Biomethane can either be injected into the gas network, providing renewable or green gas, or can be used as transport fuel. If a certification scheme exists, renewable gas or green certificates can be sold to customers to help their decarbonization efforts.

Opportunities worldwide are being explored to capture and sell removed CO_2 commercially. If this carbon dioxide is captured and stored permanently, such biomethane plants can be considered CDR technologies. Future Biogas in the UK announced plans to transform 25 of their biomethane sites in the UK into negative emission or CDR projects by capturing CO_2 and transporting it to the Northern Lights project in Norway for permanent storage in saline aquifers (Aramco 2024).

CO_2 separation from biogas is well established (TRL 9) and is already being implemented in biomethane plants (through membranes and adsorption or absorption processes). The additional step of capturing the separated CO_2 rather than releasing it into the atmosphere can also be achieved easily (examples include Air Liquide and Air Products commercial units). Biomethane plants in Saudi Arabia provide opportunities to decarbonize a small proportion of the gas grid or transport fuels while also potentially acting as CDR systems. The CO_2 captured from such plants can be transported (via roads) to either (i) central injection points on the CO_2 transport and storage network for permanent storage or (ii) to industrial sites where it can be utilized in applications such as concrete curing or green cement. However, biomethane as a renewable fuel is unlikely to be competitive with natural gas, so the feasibility of biomethane sites with or without carbon capture will depend on what incentives and certification schemes are implemented to encourage their deployment.

Both biomethane BECCS and EfW BECCS provide early entry opportunities for engineered CDR in the Kingdom. If a robust and clear waste management plant exists and diversion of waste from landfills becomes a reality, such plants can be constructed and can start operating as CDR options as early as 2030. This approach requires the deployment of a CO_2 transport and storage network, which is also a requirement for the entire CCS industry. Nevertheless, CO_2 volumes from biomethane sites are small in nature, so they can be used in industrial applications where CO_2 remains permanently stored, thus creating negative emission credits. However, the CDR requirement for Saudi Arabia from 2030 to 2060 is significant (Wang et al. 2009), and in the most optimistic scenarios[1], EfW and biomethane BECCS will be able to deliver only 20% of the CDR required in 2060 for net zero to be achieved. On this basis, other engineered CDR technologies, such as DAC, are needed.

4.2 Opportunities for DAC in Saudi Arabia

Owing to the limitations of nature-based solutions and the limited potential of BECCS, DAC has emerged as a leading option for carbon removal in Saudi Arabia. Reports on the status of DAC technology highlight its potential and opportunities for deployment (Abramson et al. 2023). A key advantage of DAC over BECCS is that it can be more freely located to remove CO_2 from the atmosphere. However, site selection for DAC should still be optimized to ensure minimal deployment costs and maximize its potential.

Owing to technology limitations and costs, the deployment of DAC on a wide scale worldwide and in Saudi Arabia is not expected to rapidly scale up in the next decade. Nevertheless, pilot-scale projects and demonstration plants are urgently needed in Saudi Arabia to exploit the first-mover advantage and develop an understanding of the associated technical, economic, and commercial challenges. In parallel with demonstrating the technology and addressing commercial, financial, governance and regulatory challenges, studies need to be undertaken to identify optimal locations for DAC plants.

The factors influencing the location of DAC sites include the following:

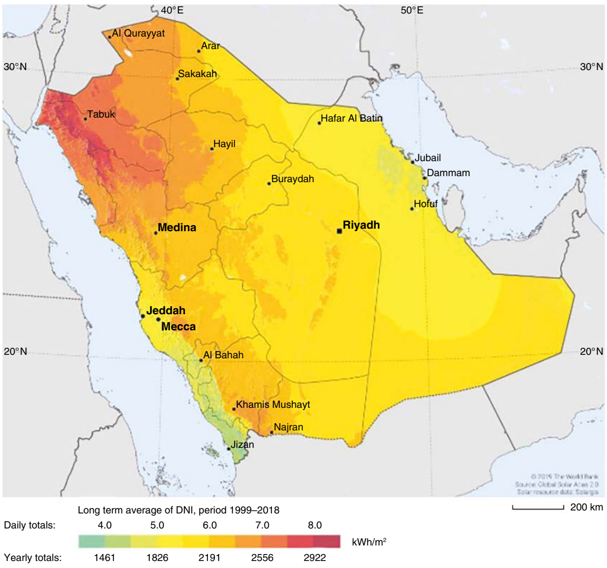
i) Waste heat availability and the availability of other low-carbon heat sources (e.g., geothermal and hot springs)
ii) Solar radiation (the potential for concentrated solar power)
iii) Renewable electricity sources (photovoltaic and wind)
iv) CO_2 storage capacity.

Available data on solar radiation, waste heat, geological storage and geothermal heat (Figure 3) can be utilized to estimate the potential for DAC in the Kingdom in various regions and thus identify the optimal locations for DAC plants. An analysis by KAPSARC (Odeh and Apeaning 2024) for the petrochemical and refinery sectors revealed that by utilizing low-grade waste heat in these two sectors and upgrading that heat for use in solid-based low-temperature DAC systems,[2] approximately 35 Mt/y of carbon dioxide removal through DAC can be achieved at an investment cost of approximately $19.2Bn (96% for DAC and 4% for heat recovery, upgrade and system refurbishment). The same principle can also be applied to other sectors where waste heat can potentially be reused. As noted above, however, this process requires significant investment costs, not only for the DAC plant itself but also for new equipment to help recover, upgrade and utilize the waste heat available. Further research is needed to estimate the full DAC potential in the Kingdom resulting from various heat and electricity sources (e.g., single source systems such as geothermal or nuclear energy as well as combined source systems, such as heat from EfW plants or geothermal sources combined with renewable electricity from solar or wind). To undertake this work, full characterization of low-carbon heat and electricity sources is needed, as shown in Figure 3. In addition, DAC site characterization requires an assessment of water availability (proximity to the sea) and atmospheric conditions, including humidity and ambient temperature.

The Eastern Province region, particularly close to the city of Damman, has the highest waste heat and CO_2 storage potential. However, another consideration in terms of locating DAC plants is that geothermal energy is available mainly on the west coast. The ideal locations for concentrated solar power (CSP) plants are in the Northern Province, while most geological storage is found near the Eastern Province. All these parameters, as well as water availability, atmospheric conditions and available technological solutions (e.g., solid-based/low temperature, SB/LT vs. carbon engineering liquid-based high-temperature, LB/HT), need to be considered in the optimization of DAC locations in Saudi Arabia and globally.

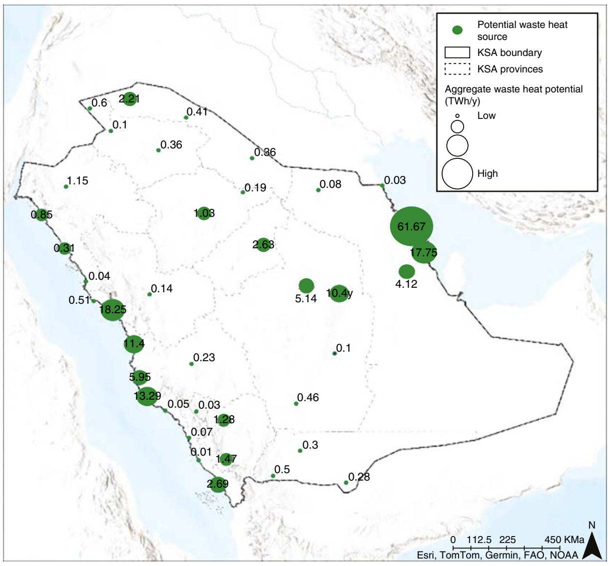
Figure 3. Parameters influencing DAC potential and costs in Saudi Arabia.

(a) Solar resources



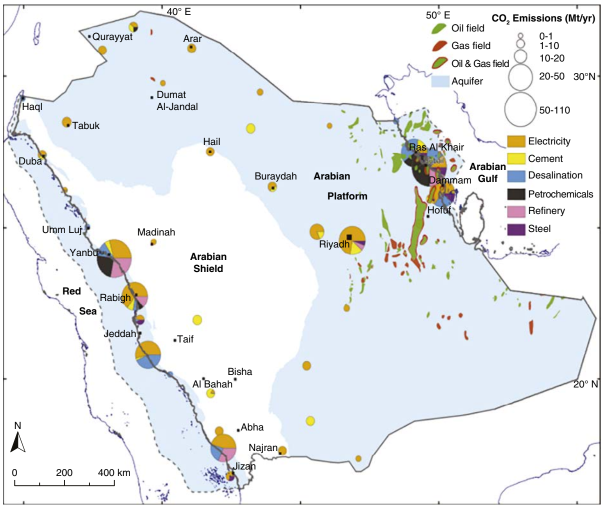
Source: KAPSARC.

(b) Waste heat potential



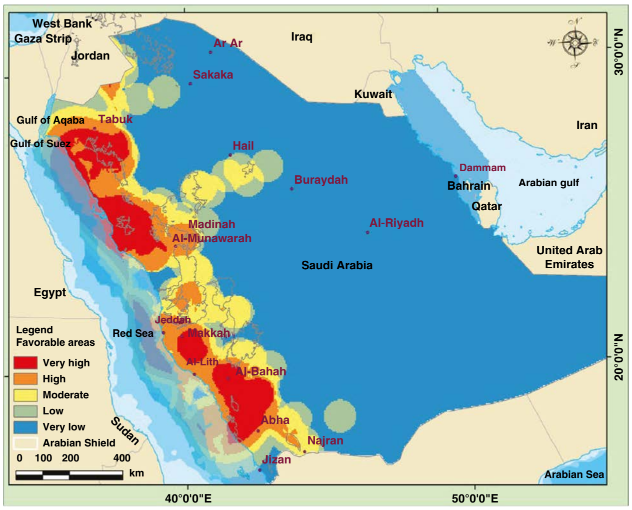
Source: KAPSARC.

(c) CO_2 geological storage capacity



Source: Ye et al. 2023.

(d) Geothermal energy



Source: Aboud et al. 2021.

5. Conclusions

The Kingdom of Saudi Arabia has demonstrated its commitment to addressing carbon removal as part of its circular economy initiatives, both domestically and internationally. A new crediting and offsetting scheme that incorporates both novel and conventional CDR methods was launched in 2023. The next steps will involve developing guidance to support its implementation. This study conducted a high-level assessment of CDR technologies and their potential applicability in Saudi Arabia, a country facing the challenges of climate change while aiming to transition its economy away from fossil fuel dependency. The findings underscore the importance of incorporating CDR options into national strategies to achieve net-zero targets effectively.

One key aspect highlighted in the analysis is the diversity of CDR solutions, which range from conventional methods such as afforestation to emerging novel technologies such as DAC, BECCS, and biochar. The MCDA methodology employed in the study provided a systematic framework for comparing these options, considering various performance, economic, and environmental criteria relevant to Saudi Arabia. Some CDR options, such as EfW BECCS, can play an early role in CDR deployment, whereas conventional CDR technologies can start to ramp up in the medium to long term. DAC and biochar will also play a role in the medium term to help achieve intermediate CDR targets. Enhanced weathering also plays a role in the longer term as technology continues to develop and its complex life cycle and environmental impacts become better understood. A key recommendation from this work is to develop a CDR strategy and roadmap for Saudi Arabia to ensure that a clear timeline is defined and that negative emission targets are achieved in the most cost-effective manner. An MRV system is also needed. This should include (i) guidance on monitoring and measuring carbon capture and storage, (ii) guidance on data recording and reporting in a transparent manner and in compliance with international standards, and (iii) a system for third party audits, validation procedures and the certification of negative emission credits. Furthermore, for the deployment of CDR technologies, a system that awards negative emissions through financial incentives (for example, government grants and subsidies, carbon pricing mechanisms, voluntary carbon markets, etc.) is needed.

DAC is an expensive CDR option that needs to be supported by BECCS, in particular EfW and biomethane plants with CCS, both of which scored highest under the MCDA analysis. EfW with CCS can serve as an early option for CDR deployment to help kickstart the CDR industry. This option is suggested since requirements are already in place in the Kingdom for diverting waste from landfills to EfW plants. Furthermore, the next decade is expected to witness the construction of EfW plants for power generation. It is thus recommended to use this opportunity to construct new EfW plants as cogeneration plants and to also equip them with CCS or to construct new plants that are carbon capture-ready. Thus, a strategy for new EfW plants in Saudi Arabia, including waste incineration, gasification and AD, is recommended, with clear guidance on planning, permitting, and operational requirements.

To achieve the announced landfill diversion rates in Saudi Arabia, while considering current waste volumes, up to 40 EfW plants (assuming a typical size of 0.5 Mt waste/y EfW plants) are expected to become operational in the next decade. These plants can be equipped with CCS and thus contribute to CDR. On the other hand, DAC is currently more expensive, with costs 2-3 times higher than those of EfW with CCS; thus, early CDR deployment in the next decade for EfW BECCS is recommended. As the costs of DAC become more attractive than those of BECCS,[3] accelerated deployment can be expected. This situation is unlikely to occur before 2035.

Owing to limitations in the potential of other CDR technologies, DAC will likely be the dominant CDR technology by 2060, contributing to a sizeable portion of the anticipated CDR requirement. Policies aimed at incentivizing the recovery of waste heat and utilizing low carbon heat for DAC processes should ensure cost optimization. Furthermore, DAC projects should be developed with low-carbon sources of electricity, including solar and wind, which can either be supplied directly to DAC plants or purchased through a renewable electricity certification system.

Overall, while BECCS and DAC solutions have emerged as options with high CDR potential, a comprehensive assessment of various CDR technologies is necessary to understand their respective roles and synergies in achieving carbon removal targets. The technoeconomic feasibility of various CDR technologies in the Kingdom should be assessed to ensure effective comparison. Furthermore, both BECCS and DAC will be complemented by nature-based solutions as the SGI target of planting 10 billion trees progresses and as more projects on wetland restoration and mangroves are implemented. New projects in planning, such as the Jizan Economic City enhanced mineralization initiative, will also contribute to future CDR targets.

This analysis emphasizes the importance of sector- and technology-specific policies to facilitate the deployment of CDR solutions. These policies should address challenges related to technology readiness, regulatory frameworks, and infrastructure development, thus ensuring a conducive environment for CDR implementation. Future CDR opportunities for Saudi Arabia include exploring technologies such as DAC, mineral carbonation, enhanced weathering, and EfW with CCS. By embracing a diverse range of CDR options and fostering innovation, Saudi Arabia can position itself as a leader in the global transition to a low-carbon economy while contributing significantly to mitigating climate change. Notably, the analysis presented here provides an opportunity for an early discussion of CDR options for the Kingdom. It differentiates these options and emphasizes the point at which engineered solutions need to be developed. It also highlights that in addition to DAC, BECCS (as EfW or biomethane) has a role in future CDR targets. Further work is needed to quantify the costs and impacts of each of these options.

The successful integration of CDR technologies in Saudi Arabia necessitates a holistic approach. Robust regulatory frameworks, policy incentives, and international partnerships are imperative to support research, development, and deployment initiatives. Encouraging private sector engagement and fostering a conducive environment for innovation and investment will further accelerate the adoption of CDR solutions.

Endnotes

[1] Assuming waste growth in parallel to population growth and assuming effective waste management practices and full diversion of waste (50% biogenic content) from landfills.

[2] The Climeworks DAC system requires temperatures in the range of 80-100°C.

[3] Assuming IEA targets for DAC will be met (60Mt/y by 2030 and 980 Mt/y by 2050) and assuming a typical learning curve of 30% for DAC, DAC costs will reach parity with BECCS between 2035 and 2040, during which wide-scale deployment globally and in Saudi Arabia can be assumed.

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About the Project

This paper, led by KAPSARC in collaboration with King Abdullah University of Science and Technology (KAUST), is part of a comprehensive project (KAPSARC references 60019) that aims to understand the potential of various CDR options in the Kingdom. This paper assesses the most relevant CDRs for Saudi Arabia. As a follow-up from this high-level assessment paper, the techno-economics and life cycle emissions of CDR solutions such as direct air capture (DAC) and EfW with CCS (EfW BECCS) will be assessed in detail. These subsequent studies will aim to assess the economics and identify opportunities for future DAC and EfW with CCS plants to help minimize CDR deployment costs.

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